

10 Irradiation Enhances Quality and Microbial Safety of Fresh and Fresh-Cut Fruits and Vegetables

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Introduction

Foodborne illness (FBI) outbreaks associated with contaminated fruits, vegetables, salads, and juices have risen more than fivefold in recent decades (Sivapalasingam and others 2004). Although preharvest (good agricultural practices, GAPs), postharvest (good manufacturing practices, GMPs) and supply-chain (good handling practices, GHPs) controls can help to reduce risk, they have not been able to prevent repeated FBI outbreaks and product recalls of tomatoes, leafy greens, melons, sprouts, and other fresh produce. It is increasingly recognized that the lack of a broadly applicable antimicrobial process (a “kill step”) is hampering the food safety efforts of the fresh produce industry (UFPA 2007; JIFSAN 2007). Conventional thermal processes cannot be applied to leafy vegetables without unacceptable damage, and existing antimicrobial chemical treatments are insufficient to adequately reduce contamination. An antimicrobial process that has come under increased scrutiny is irradiation.

Irradiation is the application of controlled doses of ionizing radiation in the form of electron beams, x-rays, or gamma rays (Table 10.1). Irradiation is a nonthermal process that kills spoilage organisms and pathogenic bacteria in a variety of fruits and vegetables (Thayer and Rajkowski 1999; Lacroix and Vigneault 2007). The safety and wholesomeness of irradiated food has been demonstrated numerous times in the 60+ years that this technology has been studied (Thayer and Rajkowski 1999; FDA 2000; Smith and Pillai 2004). In one recent example, the FDA has investigated the possibility that furan, a putative carcinogen present in thermally processed canned foods such as meats, soups, etc., might also be produced during irradiation. The safety of irradiation was reaffirmed when it was recently shown that a dose of 5 kilogray (10 kGy = 1 Mrad) did not induce detectable levels of furan in most fresh-cut fruits and vegetables (Fan and Sokorai 2008). Whereas furan production was above the limit of detection after irradiation, the levels were shown to be much lower than in thermally processed foods. Therefore, irradiation with moderate doses is as safe as thermal processing and has a potential as one of several “hurdles” in fruit and vegetable processing (Smith and Pillai 2004; Niemira and Deschenes 2005).

Fresh produce may be irradiated to inhibit sprouting, to delay ripening, to sterilize or kill insect pests, or to reduce microbial populations. Until recently, in the United States, irradiation has regulatory approval for application to produce only for insect control, sprout inhibition, and shelf-life extension. The highest dose allowed for these purposes is 1 kGy (Table 10.2). However, in 2008 the FDA (2008) approved the use of irradiation up to 4.0 kGy on fresh lettuce and fresh spinach to improve food safety

Table 10.1. Major irradiation technologies—advantages and disadvantages

Factors	Electron Beam	X-ray	Gamma
Source	Electric power Electrons are generated using electronics and accelerated to high energy using magnetic fields, 5–10 MeV ^a . When accelerator is powered off, no radiation is emitted.	Electric power Created when high-energy electrons (up to 5 MeV) strike a metal plate (e.g., tungsten or tantalum alloys); typical conversion efficiency is 5–10%. When accelerator is powered off, no radiation is emitted.	Radioisotopes Radioactive decay of ⁶⁰ cobalt (2.5 MeV) or ¹³⁷ cesium (0.51 MeV). Radioisotope source is always emitting radiation—shielding of source must be the default position.
Mechanism	High-energy electrons cleave water molecules, creating oxygen and hydroxyl radicals that damage DNA, membranes. Direct cleavage of DNA also occurs.	High-energy photons stimulate atoms within target to release high-energy electrons, which cleave water molecules into radicals. Direct cleavage of DNA also occurs.	High-energy photons stimulate atoms within target to release high-energy electrons, which cleave water molecules into radicals. Direct cleavage of DNA also occurs.
Infrastructure required	Shielding: >2 m concrete or <1 m steel/iron/lead Cooling: extensive for high-voltage electronics and accelerator Ventilation: for ozone removal while unit is operating	Shielding: >2 m concrete or <1 m steel/iron/lead Cooling: extensive for high-voltage electronics and accelerator; additional cooling systems required for plate target Ventilation: for ozone removal while unit is operating	Shielding: Depending on design, >5 m water or >2 m concrete or <1 m steel/iron/lead. Cooling: moderate for control equipment Ventilation: at all times for ozone removal when source is exposed to air
Speed ^b	Seconds	Seconds	Minutes (depending on source strength)
Penetrability ^c	6–8 cm , suitable for relatively thin or low-density products	30–40 cm , suitable for all products	30–40 cm , suitable for all products

^a MeV = million electron volts.^b Speed of dose delivery. The desired dose will vary depending on the target organism and commodity irradiated.^c Penetrability in food, avg. density approximately 1 g/cm³. This figure will vary for individual commodities due to localized variation in density associated with bone, voids, fibrous matter, etc.

and extend shelf life. The FDA is currently considering the approval of additional fruit and vegetable commodities listed in a petition filed by the Food Irradiation Coalition that would allow the produce industry to use irradiation to improve the safety of fresh and fresh-cut fruits and vegetables. If approved, treatments of up to 4.5 kGy could be applied.

Table 10.2. United States Code of Federal Regulations 21CFR179.26: Applications and dose limits for irradiated foods

Commodity and Purpose	Dose Limits
Control of <i>Trichinella</i> in pork	0.3–1.0 kGy
Suppression of growth and maturation in fresh foods	Maximum dose 1.0 kGy
Disinfestation of insect pests	Max. 1.0 kGy
Antimicrobial treatment of dry enzymes	Max. 10.0 kGy
Antimicrobial treatment of dry herbs and spices	Max. 30.0 kGy
Control of pathogens in fresh and frozen raw poultry	Max. 3.0 kGy
Sterilization of foods intended for use by NASA	Minimum dose 44.0 kGy
Control of pathogens and extension of shelf life of refrigerated and frozen meats	Max. 4.5 kGy (refrigerated), Max. 7.0 kGy (frozen)
Control of <i>Salmonella</i> in fresh shell eggs	Max. 3.0 kGy
Control of pathogens in seeds used to produce sprouts	Max. 8.0 kGy
Control of <i>Vibrio</i> species and other foodborne pathogens in fresh or frozen molluscan shellfish	Max. 5.5 kGy
Control of food-borne pathogens and extension of shelf-life of Iceberg lettuce and spinach	Max: 4.0 kGy

**Figure 10.1.** The radura logo required for labeling on irradiated foods. The logo must be accompanied by the text "treated with radiation" or "treated by irradiation."

The FDA is also considering an updating of the rules regarding required labeling for foods that have been irradiated (FDA 2000). Under the proposed rule, the radura symbol and associated text (Fig. 10.1) would be required only in those foods in which irradiation causes a material change. In this context, the term *material change* refers to a change in the organoleptic, nutritional, or functional properties of a food. Also, the FDA would allow the use of the terms *pasteurized* or *pasteurization* for a food that has been treated by irradiation, where the irradiation results in the same level of reduction as thermal pasteurization. Under current FDA rules, foods that have been

irradiated must bear both the radura logo and a statement that the food has been "treated with radiation" or "treated by irradiation."

Effective reduction of microbial load requires doses higher than for the other major purposes, and will therefore exert a larger effect on produce quality and shelf life (Farkas and others 1997). Currently, cold chain integrity and modified atmosphere packaging (MAP) are the primary means of ensuring the quality of fresh produce after it leaves the packing or manufacturing facility (Sumner and Peters 1997; Niemira and others 2005). Improper or excessive treatment of fresh produce can lead to changes in firmness, aroma, color, or taste (Yu and others 1996; Mahrouz and others 2004). Delayed effects on phytoplane microbial ecology, including behavior of contaminating pathogens, is also an important consideration (Prakash and others 2000a; Niemira and others 2004; Lacroix and Vigneault 2007). Irradiated fresh produce must adhere to accepted GAP/GMP guidelines for preservation of quality and food safety.

Quality of Irradiated Produce

Many studies have demonstrated that most fresh-cut fruits and vegetables irradiated at doses of 1 kGy or less did not exhibit any significant change in appearance, texture, flavor, or nutrient quality (Fan and Sokorai 2002a,b; Fan and others 2003a-c; Khattak and others 2006; Kim and others 2005; Yu and others 1995). Shelf life of some fresh-cut fruits and vegetables can be extended by low-dose irradiation due to the reduction of spoilage microorganisms. For example, Koorapati and others (2004) showed that irradiation at doses above 0.5 kGy prevented microbial-induced browning and blotching of sliced mushrooms. Studies have also shown that irradiated fresh produce may have higher antioxidant content than nonirradiated controls as irradiation increased synthesis of phenolic compounds (Fan and others 2005a).

In some fresh-cut fruits and vegetables, irradiation may cause softening and loss of ascorbic acid (Fan and others 2008b). However, the adverse effects on texture and ascorbic acid due to irradiation are often small compared to variation among cultivars and the changes in storage (Fan and Sokorai 2002a).

Irradiation at higher doses (above 1 kGy) often caused an increase in electrolyte leakage of many fresh-cut fruits and vegetables, an indication of cell membrane damage. The increased electrolyte leakage, which may result in a soggy and wilted appearance of leafy vegetables, varies among vegetables. In a study of thirteen vegetables, Fan and Sokorai (2005) observed that red cabbage, broccoli, and endive had the lowest increases in electrolyte leakage; celery, carrot, and green onion had the highest increase in leakage.

The losses in quality due to irradiation can be minimized by combination with other sanitizers or techniques such as MAP, heat treatment, calcium infiltration, and anti-browning agents (Prakash and Foley 2004; Niemira and Fan 2006). For example, Boynton and others (2006) showed that fresh-cut cantaloupes irradiated at 1 kGy in MAP of 4% O₂, 10% CO₂ had the highest rating in sweetness and cantaloupe flavor intensity and lowest in off-flavor after 17 days of storage compared to the control and 0.5 kGy samples. Foley and others (2004) combined chlorine (200 ppm) with low-dose radiation to eliminate *E. coli* O157:H7 on cilantro and found that the combined treatment significantly reduced levels of the pathogen on fresh cilantro while maintaining

product quality. In a sequential combination, sanitization of whole produce prior to irradiation has been shown to synergistically lower the microbial load of fresh-cut produce. Fan and others (2008a) surface-pasteurized whole cantaloupes with 76 °C water for 3 min. Fresh-cut cantaloupe pieces prepared from the pasteurized whole fruits were then packaged in clamshell containers and exposed to 0.5 kGy radiation. They found that samples treated with combined heat and low-dose radiation had lower microflora populations than either treatment alone and maintained the quality of the product. Overall, the studies conducted in the last decade demonstrated that most fresh-cut fruits and vegetables can tolerate up to 1 kGy radiation without deleterious sensory impact.

Microbial Safety of Irradiated Produce

Irradiation doses sufficient to achieve a 1-log reduction for surface-contaminating bacterial pathogens are typically in the range of 0.2–0.8 kGy. Viruses and fungi are generally more resistant, often requiring 1–3 kGy to achieve the same level of reduction (Niemira and Sommers 2006). Doses required for 3-log reductions of viruses and fungi are deleterious for most types of produce. However, it is important to recognize that the majority of serious foodborne illnesses resulting in hospitalizations and deaths (60% and 72% of the total, respectively) are attributed to bacterial pathogens (Mead and others 1999). Irradiation is therefore suitable for inactivating bacterial pathogens such as *E. coli* O157:H7, *Salmonella*, and *Listeria*, the most serious safety threats for consumers of fruits and vegetables.

Relatively low doses of irradiation can result in significant reductions of foodborne pathogens. A 1 kGy dose resulted in a 4-log reduction of total aerobic plate counts (TAPC) and *L. monocytogenes* on bell peppers (Farkas and others 1997). The same degree of reduction of TAPC was obtained on peeled, ready-to-use carrots (Lafortune and others 2005). In that study, reductions increased to 4.5 log when MAP was substituted for air packaging. A 1 kGy dose also produced a 5-log reduction of *E. coli* and *L. monocytogenes* on diced celery (Prakash and others 2000b). These studies yielded a D_{10} for these pathogens of 0.2–0.3 kGy. D_{10} values for *E. coli* O157:H7 on radish, alfalfa, and broccoli sprouts were 0.34, 0.27, and 0.26 kGy, respectively (Rajkowski and Thayer 2000). Bari and others (2004) obtained D_{10} of 0.3 kGy for both *E. coli* O157:H7 and *Salmonella* on radish sprouts, but lower values (0.16–0.18 kGy) on mung bean sprouts.

Irradiation of melons at 0.5 or 1.0 kGy reduced the microbial load and improved the keeping quality in storage (Boynton and others 2006). Apple slices treated with the antibrowning agent calcium ascorbate required higher irradiation doses to inactivate inoculated *L. monocytogenes* (Fan and others 2005b). However, the compound also protected apple slices from the negative sensory effect impact resulting from the higher dose. Irradiation of sliced carrot (2 kGy) reduced *E. coli*, *Yersinia enterocolitica*, and *L. monocytogenes* to undetectable levels (Kamat and others 2005). The D_{10} values were calculated to be 0.12 kGy for *E. coli*, 0.26 kGy for *Y. enterocolitica*, and 0.3–0.5 kGy for *L. monocytogenes*. In the same study, irradiated carrots showed insignificant losses in sucrose, total carotenes, and ascorbic acid, and had two- to fourfold increases in the refrigerated shelf life. Several isolates of *Salmonella* inoculated onto

diced tomatoes showed a D_{10} of 0.26–0.39 kGy when combined with a 1% calcium chloride dip (Prakash and others 2007).

Goularte and others (2004) obtained D_{10} values of ~0.11 kGy for *E. coli* O157:H7 and ~0.2 kGy for *Salmonella* on shredded Iceberg lettuce. Niemira and others (2002) determined that D_{10} for *E. coli* O157:H7 inoculated on iceberg, Boston, red leaf, or green leaf lettuce was dependent on which type of lettuce was examined. D_{10} in that study ranged from 0.12–0.14 kGy. In a subsequent study, the D_{10} for *Salmonella* was also dependent on the variety of the suspending lettuce and ranged from 0.23–0.35 kGy on the same four varieties (Niemira 2003). In contrast, *L. monocytogenes* did not show the same type of alteration on irradiation sensitivity. D_{10} values were invariant on the four lettuce types (0.19–0.20 kGy) (Niemira 2003). A combination of chlorination and irradiation at doses of 0.15–0.5 kGy produced fresh-cut lettuce with a reduced microbial population (Hagenmaier and Baker 1997). Although 0.81 kGy reduced the firmness of lettuce, resulting in lower shear force, 0.5 kGy or less did not affect shear force, and irradiated samples had similar shelf life as the control samples. A later study (Foley and others 2002) found that chlorination plus irradiation (5.5 kGy) reduced TAPC, yeasts, molds, and *E. coli* O157:H7 by 5.4 logs in shredded iceberg lettuce without softening of tissues.

Pathogen regrowth in storage following irradiation is a known phenomenon. Irradiation protocols must therefore be optimized within the context of GHP to ensure lasting suppression of the target pathogens throughout the storage period. Romaine lettuce, inoculated with *L. monocytogenes*, gave D_{10} values of 0.16–0.25 kGy and presented no indication of regrowth in refrigerated storage (Mintier and Foley 2006). *L. monocytogenes* was observed to regrow in refrigerated storage on endive leaves following 0.42 kGy, a dose equivalent to effecting a 2-log reduction (Niemira and others 2003). However, 0.84 kGy, equivalent to effecting a 4-log reduction, suppressed *L. monocytogenes* throughout the 19-day storage period. Combining irradiation with passive MAP was insufficient to suppress the regrowth of *L. monocytogenes* to regrow after exposure to doses of irradiation sufficient to achieve 1–3-log reductions (Niemira and others 2004). However, an active MAP using reduced- O_2 , enhanced- CO_2 effectively prevented the pathogen from regrowing after these low irradiation doses.

Protected Pathogens

Pathogens that are hidden within natural anatomical openings are often protected from chemical sanitizers and other conventional antimicrobial processes (Takeuchi and Frank 2000). Similarly, pathogens in biofilms on produce surfaces are protected from chemical antimicrobial treatments (Stewart and others 2004; Robbins and others 2005). Free-living (planktonic) cells of *L. monocytogenes* were reduced by 8 logs after a 0.5 min exposure to 10 ppm sodium hypochlorite; in the biofilm habitat, 1,000 ppm sodium hypochlorite for 20 min yielded only a 2-log reduction (Norwood and Gilmour 2000). Compared with their planktonic counterparts, biofilm-associated cells of *E. coli* O157:H7 (Ryu and Beuchat 2005), *Staphylococcus aureus* (Luppens and others 2002), and *Salmonella* (Joseph and others 2001) required orders-of-magnitude increases in treatment severity to effect adequate kill.

These results indicate that conventional processes are inadequate to address contamination by pathogens in protected areas. Irradiation, as a penetrating process, holds more promise in targeting this type of contamination, but the literature on the efficacy of this application is not extensive.

Pathogens within Biofilms

Research has recently begun to assess the ability of irradiation to inactivate internalized or biofilm-associated pathogens. Irradiation is a penetrating process, but the efficiency of irradiation in killing protected pathogens is not well known. The limited data available suggest that the particular isolate and the biofilm culture conditions (growth temperature, medium, time of cultivation, etc.) can influence irradiation efficacy. Biofilm-associated cells of *S. Stanley* and *S. Enteritidis* were significantly more sensitive to ionizing radiation than respective planktonic cells, although *S. Anatum* showed no increase in radiation sensitivity for biofilm-associated cells (Niemira and Solomon 2005). The antimicrobial efficacy of irradiation against *Salmonella* is therefore observed to be preserved or enhanced when treating biofilm-associated bacteria based on in vitro evidence. Biofilm-associated cells of *E. coli* O157:H7 ATCC 43894 grown at 37 °C for 24, 48, or 72 h were significantly more sensitive to irradiation than respective planktonic cells (Niemira 2007). *E. coli* O157:H7 C9490 biofilms grown for 24 h showed a similar increase in sensitivity; the radiation-sensitivity of biofilm-associated cells of *E. coli* O157:H7 ATCC 35150 were significantly reduced at 24 h. The response of biofilm and planktonic cells were not different for either of these two *E. coli* O157:H7 isolates in older biofilms (48 and 72 h). Biofilm-associated cells of *E. coli* O157:H7 were therefore sometimes more sensitive to irradiation and sometimes less so, with D_{10} values that varied as much as 27% above or below the D_{10} values obtained for planktonic cells. The modest amount of information that is available on the relative sensitivity of planktonic and biofilm cells to irradiation suggests a complex difference between the two physiological states of these cells (Niemira 2007). Further research in this emerging field is expected to improve our understanding of how biofilms may alter the efficacy of irradiation.

Internalized Pathogens

Pathogen internalization in produce and the resulting increase in the risk of FBI is a subject of ongoing research. Studies with lettuce (Solomon and others 2002a,b), barley (Kutter and others 2005), and maize (Bernstein and others 2007) have shown that pathogen internalization can occur when introduced via irrigation water, contaminated soil, or other means. However, other studies using tomatoes have found that internalization via the root system either does not occur, or is extremely inefficient (Jablasone and others 2004, 2005). Additional research will further improve our understanding.

Bacterial populations within a leaf, fruit, or vegetable are isolated from conventional antimicrobial treatments. A penetrating process such as irradiation may be suited to addressing this problem, although very few studies have yet investigated this. The inefficient uptake of bacteria via roots and vasculature make microbiological analysis problematic. Nevertheless, although the body of literature is relatively scant

at the present time, irradiation has been shown to eliminate pathogenic bacteria internalized within leaf tissues as a result of root uptake. Lettuce plants grown in hydroponic solutions inoculated with *E. coli* O157:H7 contained the pathogen in the leaf tissue. Irradiation effectively killed the pathogen although a treatment with 200 ppm aqueous chlorine was ineffective (Nthenge and others 2007).

As an alternative to irrigation with contaminated water, a direct inoculation method that introduces inoculum into the intracellular spaces of leaves has been developed. In these studies, irradiation was similarly effective in eliminating internalized *E. coli* O157:H7 from baby spinach and various types of lettuce (romaine, iceberg, Boston, green leaf, red leaf); 300 or 600 ppm sodium hypochlorite was generally ineffective (Niemira 2007, 2008). The limited data available suggests that D_{10} values for internalized cells (0.30–0.45 kGy) are often two- to threefold higher than for surface associated cells (0.12–0.14 kGy) (Niemira 2007). Because pathogen populations within the leaf are expected to be very low in a commercial setting, nearly absolute elimination of internalized pathogens may be practically achieved using irradiation doses that do not cause undue sensory damage. Additional research is needed to more fully understand the influence of internalization on pathogens and on the efficacy of irradiation and other treatments.

Irradiation: Not a “Silver Bullet” but a “High Hurdle”

Irradiation has sometimes been mischaracterized as a universal cure-all for microbial contamination. Although irradiation is demonstrably effective in killing bacterial pathogens, this efficacy must be practical when assessed within the context of real-world fruit and vegetable processing. The economic and commercial factors that govern other antimicrobial processes are equally relevant for irradiation of fresh and fresh-cut produce. Factors such as cost, efficiency, throughput, administrative and marketing overhead, and other issues will influence how irradiation may ultimately be used to improve the safety of fresh and fresh-cut produce. The most useful understanding of produce irradiation is to consider the commodities and products for which it is appropriate as well as those for which it may be inappropriate. Therefore, although claims to “silver bullet” status must be viewed as hyperbole, it is reasonable to regard irradiation as a “high hurdle” that can be incorporated as one important step in an overall processing plan.

Processing Considerations

A number of factors influence the antimicrobial efficacy of irradiation. The pathogen targeted, the commodity and its state of preparation (whole vs. cored, peeled, cut, chopped, etc.), type of MAP, and other product-specific factors can all modify the results of the irradiation process. Like any other industrial food-processing technology, irradiation must undergo process validation for each product being treated. Specific details such as time, temperature, handling, etc., will differ depending on commodity and purpose. For example, an irradiation process designed to eliminate *Salmonella* from tomatoes may yield unacceptable quality or microbiological results when applied, without modification or validation, for the elimination of *E. coli* O157:H7 from leafy greens.

Calculating the economic cost/benefit for produce irradiation is complex and will be specific to commodity and circumstances. The extra processing step will necessarily incur additional costs in production. These costs will differ for irradiation as a contract service with an independent irradiation facility vs. treatment with in-plant irradiation equipment. In the first case, contracting fees, shipment/transshipment costs, and time in transit are major factors. In the second case, capital costs, facility footprint, operator training, and seasonal utilization/downtime are some of the key factors. In both instances, the throughput capacity and administrative overhead will be important issues. The market benefits (brand-name protection resulting from a safer product, reduced microbial load, reduction of storage losses, premium prices commanded by specialty markets, etc.), may be offset by ancillary market drawbacks (necessity for increased public education/outreach spending, potential for increased regulatory oversight, etc.).

Packaging

Several packaging materials are approved for use in irradiation of prepackaged foods (Tables 10.3, 10.4). However, a much wider array of packaging materials currently used by the produce industry are diversified, many of which are not yet approved, such as polylactic acid, novel edible coatings, and biodegradable antimicrobial films. Because fruits and vegetables are living, respiring products, the produce industry has developed many complex packaging systems to preserve the color, texture, flavor, and

Table 10.3. United States Code of Federal Regulations 21CFR179.45: Packaging materials approved for irradiated foods

Material	Maximum Dose
Nitrocellulose-coated or vinylidene chloride copolymer-coated cellophane	10 kGy
Glassine paper	10 kGy
Wax-coated paperboard	10 kGy
Films of polyolefin or polyethylene terephthalate.	10 kGy
These may contain:	
1. Sodium citrate, sodium lauryl sulfate, polyvinyl chloride*	
2. Coatings comprising a vinylidene chloride copolymer containing a minimum of 85% vinylidene chloride with one or more of the following comonomers: acrylic acid, acrylonitrile, itaconic acid, methyl acrylate, and methyl methacrylate	
Kraft paper (only as a container for flour)	0.5 kGy
Polystyrene film	10 kGy
Rubber hydrochloride film	10 kGy
Vinylidene chloride-vinyl chloride copolymer film	10 kGy
Nylon 11	10 kGy
Ethylene-vinyl acetate copolymers	30 kGy
Vegetable parchments	60 kGy
Polyethylene film*	60 kGy
Polyethylene terephthalate film*	60 kGy
Nylon 6 films*	60 kGy
Vinyl chloride-vinyl acetate copolymer film*	60 kGy
Acrylonitrile copolymers*	60 kGy

*This material may be amended with additional materials, listed in Table 10.4.

Table 10.4. United States Code of Federal Regulations 21CFR179.45: Adjuvants and amendments approved for incorporation into certain packaging materials approved for irradiated foods

Adjuvant/Amendment	Limit (by Wt. of Polymer)
Amides of erucic, linoleic, oleic, palmitic, and stearic acid.	1%
BHA (butylated hydroxyanisole)	1%
BHT (butylated hydroxytoluene)	1%
Calcium and sodium propionates	1%
Petroleum wax	1%
Mineral oil	1%
Stearates of aluminum, calcium, magnesium, potassium, and sodium	1%
Triethylene glycol	1%
Polypropylene, noncrystalline	2%

aroma of these commodities. New packaging materials and new combinations of existing materials are brought to market each year. This poses a challenge for the regulatory review and approval process for irradiation of packaging. For example, polyethylene terephthalate (PET) films are approved by the FDA under 21 CFR 179.45, but rigid and semirigid PETs are not. In cases where the use of the new packaging material in the food-contact article results in a dietary concentration at or below 0.5 ppb, the FDA will consider requests to expand the permissible packaging materials for irradiated foods. However, the processing conditions that must be met for such exemptions to be granted (max. dose <3 kGy, oxygen-free packaging or vacuum-frozen product) are usually not appropriate for fresh produce. New packaging materials that are not currently approved for irradiation, such as biodegradable and antimicrobial packages, adjuvants (antioxidants, stabilizers, etc.), plasticizers, colorants, and adsorbent pads may need more research before being evaluated and approved by the FDA (Komolprasert 2007).

Consumer Acceptance

Commercial adoption of food irradiation has been limited. Foods that are approved for irradiation make up a relatively short list. Uncertainties regarding the cost of the process and consumer reluctance contribute to this, despite encouraging market research data. Consumers are more willing to buy irradiated foods after they are provided information about the process, with 50% or more willing to buy irradiated food if given the option (Bhumiratana and others 2007). Consumer education is the most influential factor in the purchasing decision. A recent survey of different elements within the produce industry found differences in acceptance of produce irradiation (Anonymous 2007). A majority (63%) of growers/shippers believe that the produce industry should push for irradiation or similar treatments, as long as product quality can be preserved. Among packers, 40% supported irradiation and 40% were undecided. A minority (30%) of growers/shippers think consumers would currently purchase irradiated leafy greens and other produce. At the retail level, only 25% of retailers believe there is consumer acceptance for irradiated produce and only 7% of retailers actually stock irradiated produce. Education and outreach to retailers and

consumers may be an initial requirement to advance the commercial applications of irradiation for fresh produce.

Summary

Irradiation is a nonthermal kill step that has great potential for application to fresh and fresh-cut produce. Used as part of an overall program of GAP, GMP, and GHP, irradiation can serve as an important tool in preserving the safety and quality of produce. The wide and expanding range of fruit and vegetable products on the market presents both a challenge and an opportunity for processors wishing to evaluate irradiation. Process validation, including commodity preparation methods, storage conditions, and market forces will identify the appropriate venues for irradiation to be employed. Ultimately, irradiation can play an important role in the production of safe, high-quality produce.

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